FIRST RESULTS ON A TRANSATLANTIC TIME AND FREQUENCY TRANSFER BY GPS CARRIER PHASE

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Abstract

Time and frequency transfer by GPS carrier phase, also referred to as Geodetic Time Transfer (GeTT), has been studied intensively in the frame of a collaboration between the Swiss Federal Office of Metrology (OFMET) and the Astronomical Institute of the University of Berne (AIUB). Two terminals equipped with geodetic GPS receivers have been built and were successfully deployed over European baselines. The study has demonstrated the low instrumental noise of GeTT ($\sigma_y(\tau) = 10^{-13}$ at $\tau = 100$ s) which makes this method an ideal tool for frequency comparisons between high performance clocks since much shorter averaging times are required than with GPS common view.

This new time and frequency transfer method is now to be tested over longer baselines. In this paper we report on a transatlantic campaign between the Physikalisch-Technische Bundesanstalt in Germany (PTB) and the US Naval Observatory, Washington (USNO). Besides the longer baseline the choice of these two sites offers also the possibility to compare frequently GeTT and TWSTFT.

The paper outlines the main parts of a GeTT campaign and summarizes the first results of time and frequency transfer by GPS carrier phase between PTB and USNO.

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INTRODUCTION

The GPS Common View (CV) and the Two Way Satellite Time and Frequency Transfer (TWSTFT) are up to now the most used methods for precise time and frequency transfer. In parallel with the development of new types of frequency standards achieving outstanding performances, there is a demand for new tools to compare these devices. Requiring only receiver capabilities on either side of the comparison, the CV method is relatively simple to use. However, an averaging time of at least a few days is needed to compare the new frequency standards at their best levels. On the other hand, the TWSTFT technique allows comparisons with a shorter time but at the prize of heavy sending and receiving equipment on each site.

An interesting alternative to associate simplicity and precision is to use geodetic GPS receivers [1]. Since only code information is processed in the CV technique while carrier phase information is discarded, the GPS is not used to its full potential in time and frequency transfer. The approach to record all GPS observables (Code CA, P1, P2, phase L1, L2) is well established in the geodesy community where these observations are carried out routinely in the framework of the International GPS Service for Geodynamics (IGS) [2]. Powerful tools have been developed to deal with the problem of phase ambiguity, ionospheric and tropospheric delays and satellite orbits. It is thus natural to seek for improvement of the time and frequency transfer by GPS in a collaboration between the geodesy and the time and frequency communities. The recent IGS - BIPM pilot project [3] is a perfect example of a joint effort in this direction.

As a precursor to the IGS-BIPM project, a collaboration between the Astronomical Institute of the University of Berne (AIUB) and the Swiss Federal Office of Metrology (OFMET) has led to the development and construction of two terminals and the processing software for geodetic time transfer (GeTT).

CAMPAIGN SETUP

A typical configuration of a GeTT campaign is shown in Figure 1. A GeTT terminal is placed on each site participating in the campaign. For simplicity, only two sites are drawn in Figure 1 but more stations could be included and treated simultaneously. The local clocks to be compared provide a 5 MHz signal and a 1 PPS. Each station acquires all 5 GPS observables every 30 s and sends the results daily to the processing center via FTP. A detailed description of a GeTT terminal can be found *e.g.* in [4]. Taking into account the precise orbits of the satellites and information on ionospheric and tropospheric delays, the processing center computes for each observation the delay between an arbitrarily chosen reference station and all other participants. The final GeTT results are computed 5 days after the observations when the IGS products become available.

For the study of this paper, a first GeTT station has been placed at the PTB in Braunschweig, D. It will be labeled PTBA throughout the paper. A second is installed at the USNO, Washington, USA, and is referred to as USNB. The baseline between the two receivers measures 6'275 km. At the PTB, the local clock connected to the station is a hydrogen maser (Kvarz CH1-75, labeled H2), the same clock that is used for the TWSTFT measurement. This maser is free running and not steered to follow the local timescale. However, a local comparison every 30 minutes between the maser H2 and UTC(PTB) allows to perform time transfer experiments. The local clock at the USNO is also a hydrogen maser (MC2), but in contrast to the PTB

configuration this maser is corrected once a day to follow UTC(Mean), which is a steered time-scale [7]. Local comparisons at the USNO to connect UTC(USNO) to other stations are, therefore, not necessary. Both stations were installed around MJD 51014 and the campaign will probably last beyond the end of 1998.

FREQUENCY TRANSFER

Let us first assess the frequency transfer capabilities of GeTT over the transatlantic baseline. Since only relative frequency is of interest here, the local comparisons at the PTB between the maser H2 and UTC(PTB) are not taken into account. Figure 2 summarizes the main results of this part of the study in the form of an Allan variance diagram. The black triangles give the comparison of H2 at PTB and MC2 at USNO by GeTT. Typical individual performances of the participating clocks are represented by diamonds (H2 at PTB) [6] and triangles (MC2 at USNO) [7]. The circles, finally, indicate a comparison between PTB and USNO by means of GPS CV. For this purpose, out of the set of unequally spaced CV observations, one value was computed every 6 hours.

Several important features have to be emphasized on this graph. First, for averaging times of 10^4 s up to 10^5 s, both local clocks, the masers at the PTB and at the USNO, have a relative frequency stability in the 10^{-15} range and, thus, do not represent a limiting factor for the experiment. Secondly, it has to be noted that GeTT performs, as expected, better than classical GPS CV for all averaging times displayed. For short τ (< 10^5 s), the improvement gained by GeTT is at least one order of magnitude. This result is of great practical importance. If 2 clocks at the 10^{-14} level are to be compared, averaging times of up to 10^6 s (> 10 d) are required with GPS CV, while $3 \cdot 10^4$ s (< 1 d) are sufficient with GeTT. This makes this tool suitable for the comparison of clocks of the upcoming generation of primary frequency standards. Another important and surprising point is the observed slope on the $\sigma_y(\tau)$ plot for GeTT. The instrumental noise of CV averages with τ^{-1}, indicating phase noise. For GeTT, however, the $\sigma_y(\tau)$ decreases with $\tau^{-1/2}$, a signature for white FM. Since both clocks are significantly below the noise level computed with GeTT, the slope -1/2 must be ascribed to the method. While the mechanism leading to this behavior is not fully understood yet, some elements of explanation can nevertheless be pointed out. In order to verify if the excessive noise is due to the long baseline between PTB and USNO, a comparison with another station was undertaken. This third station, also located at the USNO, is not a dedicated GeTT terminal but part of the IGS network [2] in which it is labelled USNO. It is steered by a different maser than USNB. Figure 3 shows the delay between the stations USNO and USNB as measured with GPS carrier phase. In fact, since all delays in the present setup are given against PTBA, the difference USNB -USNO is obtained by evaluating (PTBA - USNO) - (PTBA - USNB). Discontinuities in the delay are clearly visible in the graph at the transition between consecutive days. These jumps are the consequence of a discrete offset correction which is calculated every day to bring the average phase solution in agreement with the average of the code. Odd behavior of the code on a given day induces large differences between the offset of two consecutive days and causes the observed discontinuities. A good example of such a behavior is Day of Year (DoY) 280. If the Allan variance is calculated for a set of delays between USNO and USNB as displayed in Figure 3, the level of noise for short τ is identical for this short baseline to the $\sigma_y(\tau)$ observed for PTBA - USNB. To make the influence of these jumps on the Allan variance even clearer, especially for $\tau < 10^4$ s, data of a single day were used, thus avoiding entirely the discontinuities.

The resulting Allan variance is displayed in Figure 4. Since no jumps are present in this subset of data, it is not surprising that the noise level of the Allan variance is lower. But in addition to the lower noise, the slope for $\tau < 5 \cdot 10^3$ s is also steeper than previously. It is also interesting to note that even though the comparison USNB - USNO is obtained over the detour of PTBA the noise is similar to the one measured in a common clock experiment over a zero-baseline campaign (long dashes in Figure 4).

For longer baselines, however, more elements seem to be of importance. This becomes apparent in Figure 4 where the Allan variances for other comparisons with different baselines are shown as well. As before, two IGS stations (USNO and NRC1 at the NRC in Canada) have been used for this study. These are not dedicated stations for time and frequency transfer but rather permanent receivers of the IGS network. Both stations are steered by hydrogen masers. The table below gives an overview of the baselines between USNB and the other stations.

Location	Name of station	Baseline with USNB (km)
Washington, USA	USNO	~ 0
Ottawa, Canada	NRC1	735
Braunschweig, D	PTBA	6'275

Again, data of one day only are used to avoid the jumps described above. The lowest curve in Figure 4 is again the comparison over the near-zero-baseline USNO-USNB. Slightly higher is the comparison between USNB and NRC1. For the largest baseline between USNB and PTBA, the Allan variance shows again the $\tau^{-1/2}$ dependence even though there are no discontinuities present in the data set. It has to be noted, however, that only one single day of data has been processed and that the behavior could vary from day to day. Systematic measurements will be necessary to answer this question definitely.

A last striking feature in Figure 2 is the excessive noise for 10^5 s $< \tau < 10^6$ s. The contour of the $\sigma_y(\tau)$ of the comparison for $\tau > 3 \cdot 10^5$ s can be reproduced perfectly by the Allan variance of a sine wave with a period of $1.45 \cdot 10^6$ s (16.8 d). Since this is an uncommon period for GPS measurements, it is unlikely that this behavior is due to the GeTT method itself. Individual performances of the participating clocks, however, do not show any evidence for an oscillation either. More investigations are required to explain the observed excess noise, including a comparison with other stations.

TIME TRANSFER

A second important part of the study is the time transfer experiment. Besides the fact that both institutions, PTB and USNO, maintain an excellent timescale, the choice of these sites offers the further advantage that a TW time transfer is routinely carried out between both parties. Observations take place 3 times a week, on Monday, Wednesday and Friday. The goal of this part is to demonstrate the time transfer capabilities of GeTT. As already mentioned above, the GeTT terminal at the PTB is not steered by UTC(PTB), but by a free running maser. To be able to correct for the delay UTC(PTB) - H2, a local measurement is performed every 30 minutes. The same clock H2 is also used in the TWSTFT experiment at the PTB. At the USNO, local comparisons are not required, since the maser steering TWSTFT and GeTT is corrected to follow UTC(USNO).

The results of the comparison of the two timescales are represented in Figure 5. The white circles stand for the data obtained by TWSTFT [9]. Over the displayed period of 80 d, 24 successful TWSTFT sessions were carried out between PTB and USNO (out of a scheduled maximum of 34). Each data point represents the average of the data collected over one TWSTFT session lasting 120 s. The black curve gives the GeTT results of which 2880 are taken per day. To speed up the processing time, the delays are calculated every 300 s only, reducing the amount of data by a factor of 10. Uncalibrated internal delays of the GeTT terminal have made it necessary to shift the raw data by a fixed amount of -112.9 ns to fit the GeTT results to the TWSTFT. The third curve in gray is added to the graph to visualize the difference of transfer by GeTT and by GPS CV. On average, 15 CV observations per day are possible between PTB and USNO. These data have again been shifted to match the TWSTFT results (shifted data = raw data - 24.4 ns). It is easiest to analyze the time transfer capabilities if the difference between the transfer by TWSTFT and the transfer by the alternative method is built. The two curves of Figure 6 correspond to $transfer_{GeTT}$ - $transfer_{TW}$ (black triangles, connected by a solid curve to guide the eye) and to $transfer_{CV}$ - $transfer_{TW}$ (white squares, connected by a dotted line). For this graph, no averaging has been performed on the GeTT data. Displayed are simply the differences between the GeTT result corresponding to the epoch for which a TWSTFT result exists and the TWSTFT result itself. For the difference CV against TWSTFT, a linear interpolation was used to compute the delay measured by CV at the epoch for which a TWSTFT result is available.

Having shifted CV and GeTT data, the absolute value in Figure 6 can not be of interest. What is more important is the constancy of the difference and, thus, the internal delays. The delays in the GeTT terminals seem to be insensitive to an interruption of the acquisition. On two occasions (DoY 238 and DoY 258) over the period of interest, the method failed to acquire data continuously. The delays seem not to have changed after the restart since no discontinuity can be observed on these days. Let us point out that the spread of the result GeTT - TWSTFT is significantly smaller than that of the difference CV - TWSTFT. As expected, GeTT outperforms GPS CV as a time transfer tool.

However, the difference between the time transfers by GeTT and TWSTFT respectively is drifting with an average slope of +43 ps/d. The origin of this slope is not known. Since Figure 6 displays differences of comparisons by two distinct methods which are steered by the same clocks, the only possible explanation for the slope is a drift of a delay in one or the other time transfer system. Delays in the antenna and the cables are known to change with temperature, but the coefficients for GeTT [8] are not large enough to explain the observed slope. It is also difficult to draw conclusions from the difference CV - TWSTFT, mainly due to the large spread of the data. More work is needed to explain the origin of the drift between GeTT and TWSTFT.

CONCLUSION

The possibility of time and frequency transfer by GPS carrier phase between the PTB, Braunschweig, D and the USNO, Washington, USA has now been studied over a period of 4 months. The study has proven the feasibility of this technique over transatlantic distances and shown a good reliability throughout the campaign. The hardware of GeTT is only slightly more complicated than classical GPS CV, but for short

averaging times GeTT outperforms GPS CV by at least one order of magnitude. The price to pay is a more sophisticated processing of the data. However, the required tools exist and have already proven their adequacy to handle the large amount of data in a network of over 10 stations. A frequency transfer at the level of 10^{-13} for $\tau = 300$ s was possible over the 6'275 km long baseline of this study. At present, this limit seems to be imposed by the data processing. As for the time transfer the results look very promising as well. The main goal of this part of the study was to check the constancy of the different local delays. The difference of the time transfer by GeTT and the time transfer by TWSTFT has drifted with a slope of 43 ps/d over the period of 80 observed days. It remains unclear whether this slope must be ascribed entirely to GeTT or if the involved TWSTFT contributes also to this difference. More work needs to be done on this topic. It is also important to note that in the present setup not all local delays are known and that, therefore, it is impossible to carry out absolute time transfer. In spite of this, GeTT is certainly an interesting additional tool for time and frequency transfer, especially due to its quasi-continuous acquisition of data which makes an uninterrupted comparison between remote timescales possible.

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[9] The TWSTFT data used for this graph are available in standard format from FTP sites at the PTB and the USNO.

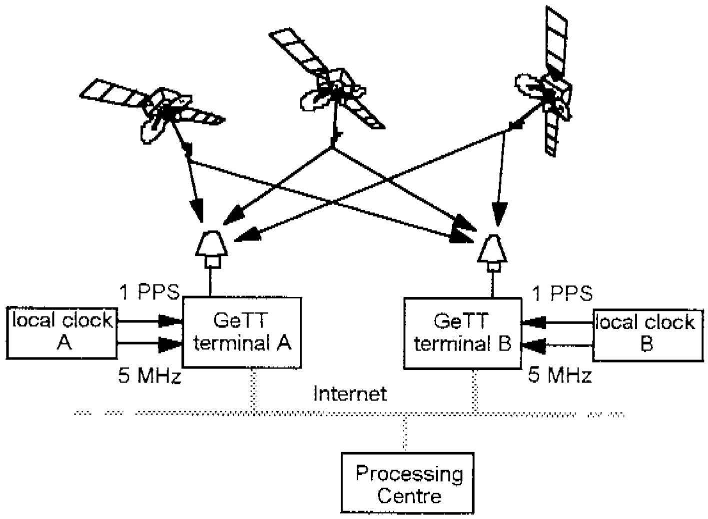

Figure 1: A typical configuration of a GeTT campaign. On each site, a GeTT terminal is installed and connected to the local clock to be compared. Acquired data are sent daily via FTP to the processing center which delivers the delay between the arbitrarily chosen reference station and all other participants 5 days after the observations.

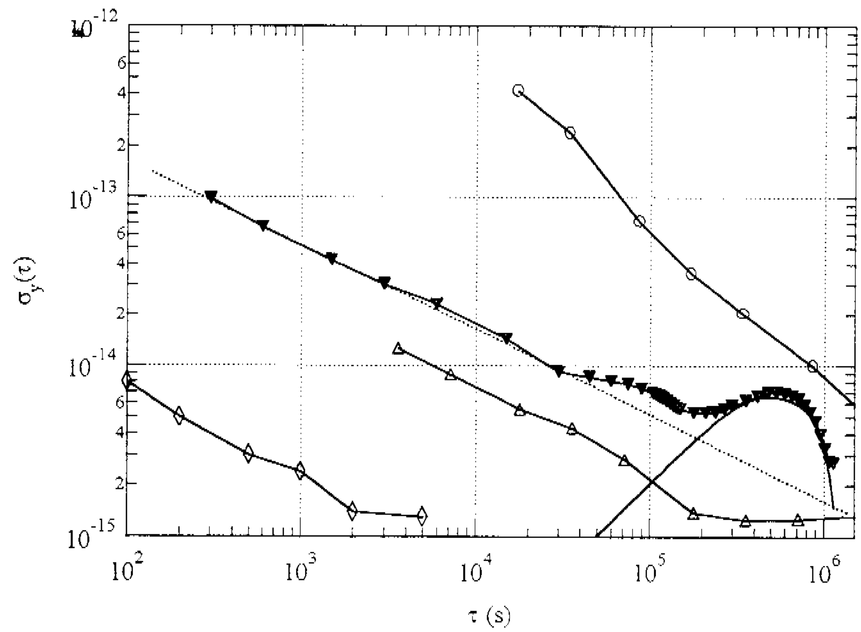

Figure 2: Allan variance for the comparison H2 - MC2 by GeTT (black triangles), the local clocks H2 at PTB (diamonds) and MC2 at the USNO (white triangles). The white circles represent the Allan variance for a comparison between PTB and USNO by GPS CV (not with the same clock sources). The plain line without symbols shows the $\sigma_y(\tau)$ for a sine wave with amplitude 2.2 ns and a period of $1.45 \cdot 10^6$ s.

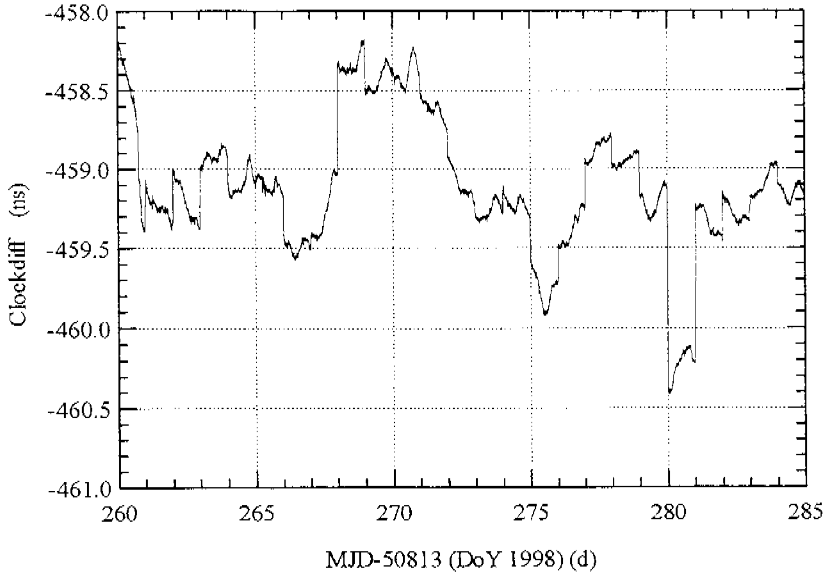

Figure 3: Delay between USNB and USNO as measured by GeTT. Discontinuities discussed in the text are clearly visible

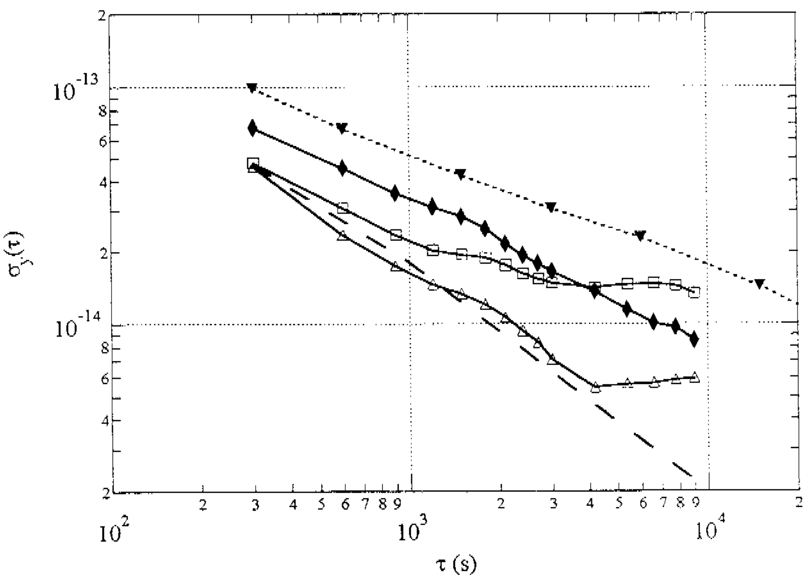

Figure 4: Allan variance computed with only one day of data for different comparisons: USNB-USNO: white triangles; USNB -NRC1: white squares; PTBA - USNB: black diamonds. For purpose of comparison the Allan variance for the complete set of data PTBA - USNB is also indicated (short dashes, inverted black triangles). The instrumental noise of GeTT, as measured over a zero baseline in a common clock experiment, is indicated by the long dashed line.

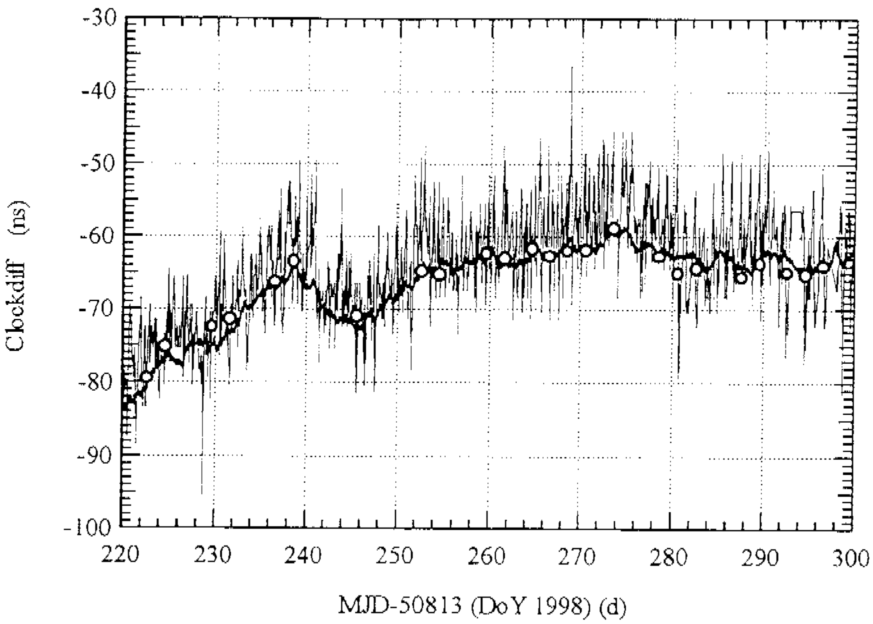

Figure 5: Difference of the timescales at PTB and USNO by a) TWSTFT in white circles, b) GeTT, black curve, c) GPS CV in gray. The result of GeTT has been shifted by -112.9 ns, those of CV by -24.4 ns, both to match the result of TWSTFT.

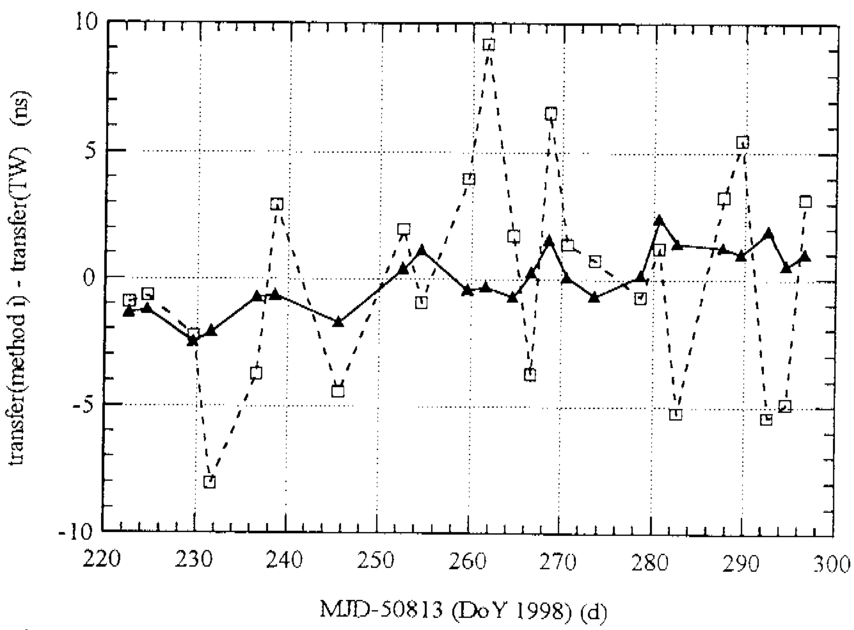

Figure 6: Black triangles: Difference between the time transfer by GeTT and the time transfer by TWSTFT
White squares: Difference between the time transfer by CV and the time transfer by TWSTFT.

Questions and Answers

JIM DeYOUNG (USNO): Perhaps I missed it, but at PTB the distance between the two-way antenna and the clock hall is quite a long distance, 100 meters to 150 meters, or perhaps more. Can you tell me the location of where the Ashtech – or whatever antenna you use, what is the location of it? Is it on the clock hall?

GREGOR DUDLE (Swiss Federal Office of Metrology): It is almost in the clock hall. We use approximately 40 meters of cable, so it is not very far away.

DIETER KIRCHNER (TUG): When you say you have carrier phase measurements every 30 seconds, is this an average over 30 seconds?

GREGOR DUDLE: No, no. This is just the 30-second observations. We have an observation every 30 seconds.

DIETER KIRCHNER: So, there is no averaging.

GREGOR DUDLE: No.

ROBERT DOUGLAS (NRC): When you say that it is an independent measure; what is the initial point for the integration? Because, you are integrating the carrier phase ---

GREGOR DUDLE: I am not the expert on the data processing. Maybe we can discuss the data processing problem after this session.